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Combined effects of climate change and sea-level rise project dramatic habitat loss of the globally endangered Bengal tiger in the Bangladesh Sundarbans

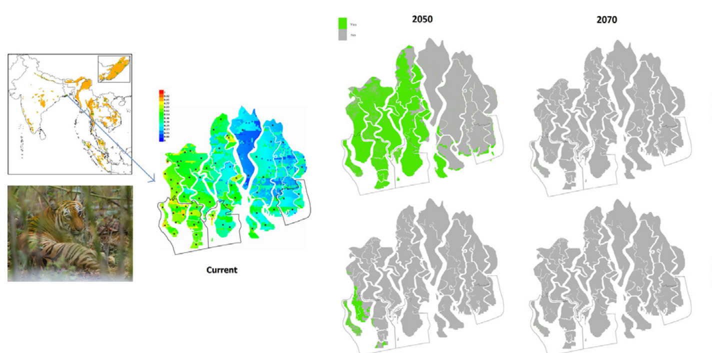
Sharif A. Mukul [a,b,c,*], Mohammed Alamgir [d,e], Md. Shawkat I. Sohel [b,c], Petina L. Pert [f], John Herbohn [b,c], Stephen M. Turton [g], Md. Saiful I. Khan [h], Shifath Ahmed Munim [a], A.H.M. Ali Reza [i], William F. Laurance [d]

[a] *Department of Environmental Management, School of Environmental Science and Management, Independent University Bangladesh, Bashundhara R/A, Dhaka 1229, Bangladesh*
[b] *Tropical Forests and People Research Centre, University of the Sunshine Coast, Maroochydore DC, QLD 4558, Australia*
[c] *Tropical Forestry Group, School of Agriculture and Food Sciences, The University of Queensland, Brisbane, QLD 4072, Australia*
[d] *Centre for Tropical Environmental and Sustainability Science, College of Science and Engineering, James Cook University, Cairns, QLD 4878, Australia*
[e] *Institute of Forestry and Environmental Sciences, University of Chittagong, Chittagong 4331, Bangladesh*
[f] *CSIRO Land and Water, Douglas, QLD 4814, Australia*
[g] *Central Queensland University, Cairns, QLD 4870, Australia*
[h] *Department of Zoology, Otago University, Dunedin 9054, New Zealand*
[i] *Department of Biological Sciences, Delta State University, Cleveland, MS 38733, USA*

HIGHLIGHTS

- The likely future distribution of Bengal tiger in the Sundarbans forest was modeled using IPCC RCP6.0 and RCP8.5 scenarios.
- Our results suggest a rapid decline in the Bengal tiger population and suitable habitats in the Sundarbans.
- By 2070, there will be no suitable tiger habitats remaining in the Bangladesh Sundarbans.
- Climate change will have a more pronounced effect on tiger habitats than that of sea level rise in the area.

GRAPHICAL ABSTRACT



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ABSTRACT

The Sundarbans, in southern coastal Bangladesh, is the world's largest surviving mangrove habitat and the last stronghold of tiger adapted to living in a mangrove ecosystem. Using MaxEnt (maximum entropy modeling), current distribution data, land-use/land cover and bioclimatic variables, we modeled the likely future distribution of the globally endangered Bengal tiger (*Panthera tigris tigris*) in the Bangladesh Sundarbans. We used two climatic scenarios (i.e., RCP6.0 and RCP8.5) developed by the Intergovernmental Panel on Climate Change (IPCC) to provide projections of suitable habitats of Bengal tigers in 2050 and 2070. We also combined projected sea-level rise for the area in our models of future species distributions. Our results suggest that there will be a dramatic decline in suitable Bengal tiger habitats in the Bangladesh Sundarbans. Other than various aspects of local climate, sea-level rise is projected to have a substantial negative impact on Bengal tiger habitats in this low-lying area. Our

* Corresponding author at: Department of Environmental Management, School of Environmental Science and Management, Independent University Bangladesh, Bashundhara R/A, Dhaka 1229, Bangladesh.
E-mail address: smukul@iub.edu.bd (S.A. Mukul).

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Climate change
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model predicts that due to the combined effect of climate change and sea-level rise, there will be no suitable Bengal tiger habitat remaining in the Sundarbans by 2070. Enhancing terrestrial protected area coverage, regular monitoring, law enforcement, awareness-building among local residents among the key strategies needed to ensure long-term survival and conservation of the Bengal tiger in the Bangladesh Sundarbans.

1. Introduction

Climate change has already threatened biodiversity worldwide with many species already responding to recent climatic shifts (Pimm, 2008; Heller and Zavaleta, 2009; Dawson et al., 2011; Garcia et al., 2012; Aryal et al., 2015, 2016a). Climate change has direct impacts on biodiversity by shaping species habitat range (Colwell et al., 2008), their survival (Chamaille-Jammes et al., 2006), resource availability (Visser and Both, 2005) and interactions among species (Moritz and Agudo, 2013). The relative impacts of climate change on wildlife varies by region, with previous studies focusing on particular regions or species (see - Colwell et al., 2008; Costion et al., 2015; Struebig et al., 2015a, 2015b; Alamgir et al., 2015; Wich et al., 2016).

Globally, anthropogenic climate change has already led to a warmer temperature, changing precipitation, and more frequent extreme weather events (Bindoff et al., 2007; IPCC, 2014). Sea level rise (SLR) associated with climate change likely to also adversely affect the biodiversity and wildlife habitats in coastal low-lying regions (Nicholls and Cazenave, 2010). Tropical Asia is one of the most vulnerable regions to climate change and SLR with yet one of the highest rates of deforestation in the world (Hansen et al., 2013; IPCC, 2014). The region is also home to a large number of threatened and endemic species making it critical for integrated assessment and planning for effective conservation in the context of climate change and associated events (Kaeslin et al., 2012; Stanton et al., 2015; Apan et al., 2017).

Tiger (*Panthera tigris*) is the largest predator in Asia and historically distributed across much of the continent (Walston et al., 2010a; Fig. 1). The global number of the tiger is now as few as 3890 individuals (WWF, 2016), although these wild tigers are mostly found in the protected areas (Wikramanayake et al., 1998; Walston et al., 2010b). Approximately 1.5 million square kilometres (km^2) tiger habitats remain now, representing only about 7% of their historical range (Dinerstein et al., 2007; Walston et al., 2010a). Habitat loss, hunting, and illegal trade of tiger parts have decimated the number of wild tigers by 96% from nearly 100,000 individuals on 1900s (Dinerstein et al., 1997; Kitchener and Dugmore, 2000). In recent years, international conservation and donor agencies together with the governments have initiated programs to address this issue and to increase tiger persistence outside of the protected areas (see - Aryal et al., 2016b; WWF, 2016; Thapa et al., 2017). Of the eight subspecies of tiger, three (i.e., *Panthera tigris balica*; *Panthera tigris virgata*; *Panther tigris sondaica*) have already gone extinct (Luo et al., 2004) and the rest are either endangered or critically endangered (IUCN, 2015).

The Bengal tiger (*Panther tigris tigris*) is one of the sub-species of tiger that is geographically restricted to Bangladesh, Bhutan, India, Nepal, and Myanmar (Ranganathan et al., 2008; IUCN, 2015). The Bengal tiger also represents the largest remaining population (~67%) of wild tigers in the world (WWF, 2016). The Sundarbans mangrove forest, the world's largest contiguous mangrove forest shared between Bangladesh and India with an area of about 10,263 km^2, is also the world's only mangrove forest with tigers and the largest remaining Bengal tiger habitats in the world (Ifthekar and Islam, 2004; Dinerstein et al., 2007; McGregor, 2010). The Sundarbans, due to its geographic location is one of the world's largest and dynamic delta system and also at the forefront of climate change and related events (Sarwar, 2013; MoEF, 2016). Climate change has already caused changes in vegetation (Mukhopadhyay et al., 2015), salinity (Hoque et al., 2006) and sedimentation (Syvitski et al., 2009) in the Sundarbans. The mean elevation of most of the Sundarbans is less than one meter (m) above sea level (asl), making it also highly vulnerable to SLR (Canonizado and Hossain, 1998).

Preparing for impacts of climate change must be based on insight from real world actions, considering the complex interactions between species and the physical environment (Ockendon et al., 2014). Here we investigate the likely future distribution of Bengal tiger in the Bangladesh Sundarbans under changing climatic scenarios. A previous study considering only SLR found a dramatic decline in suitable habitats for tigers in the Sundarbans mangrove forest (see Loucks et al., 2010). Our study jointly addresses the issue of changing climate and SLR on Bengal tigers - a globally important conservation flagship species in

Fig. 1. a) An illusive Bengal tiger laying in the forest (Photo: Rakesh Narala), b) vegetation pattern in the Sundarbans (Photo: Sharif A. Mukul), and c) the major prey species - spotted deer in the Sundarbans (Photo: Sayam U. Chowdhury).

one of the world's active delta system and largest mangrove forest. Identifying the extent to which Bengal tigers could be affected by climate change and SLR is important both for their conservation and effective management (Bellard et al., 2016), and also critical to understand the impacts of climate change on large predators in mangrove ecosystems.

2. Materials and method

2.1. The study area

The Bangladesh Sundarbans (hereafter refer to as 'the Sundarbans') covers an area of about 6017 km^2, nearly 60% of the total area of the Sundarbans (Fig. 2). The area is under the jurisdiction of the Forest Department (FD), and designated as a reserved forest. Geographically Sundarbans is situated on the lower Ganges-Brahmaputra delta, the world's second largest watershed system (Ericson et al., 2005). There are three wildlife sanctuaries in the Sundarbans, i.e., Sundarban West (715 km^2), Sundarban South (370 km^2), and Sundarban East (310 km^2). The area is also a UNESCO World Heritage Site and a Class 3 tiger conservation landscape of global priority (Dinerstein et al., 2006).

The climate in the area is humid tropical with a mean annual rainfall about 1700 mm and annual temperature ranging between 29° and 31 °C (Gopal and Chauhan, 2006). The area experiences severe tropical cyclones almost every year, originating from the Bay of Bengal, which acts as a natural barrier during their landfall (Harun-or-Rashid et al., 2009). At least 334 species of plants, 49 mammals, 59 reptiles, 8 amphibians, and 315 bird species have been recorded from the area (Ifthekar and Islam, 2004; Aziz and Paul, 2015). The vegetation of the area is dominated by halophytic species (Biswas et al., 2007; Mukhopadhyay et al., 2015). Three species, i.e., *Heritiera fomes*, *Excoecaria agallocha* and *Ceriops decandra* represents approximately 95% of the vegetation in the area (Ifthekar and Saenger, 2008; Fig. 2; Table S1).

Of the total area of the Sundarbans, about 30% is comprised of a complex network of rivers and streams of varying depth and width (Islam et al., 2014). The elevation of most of the Sundarbans varies from 0.5 m to 3.0 m asl with nearly 70% of the area under 1 m asl (Siddiqi 2001; Khan, 2013; Table S2). The majority of the vegetation in the area inundated by water twice a day during regular tidal flooding (Khan, 2013). The salinity also varies within the Sundarbans and are less saline (oligohaline) on the eastern part and more saline (polyhaline) on the western part (Hoque et al., 2006; Fig. 2). The soils of the area are finely textured with silty clay loam (Choudhury, 1968).

2.2. Bengal tiger distribution data

The Bangladesh Sundarbans has a tiger occupancy of 4832 km^2 (Barlow et al., 2008). A previous study using radio collar and satellite tracker identified home ranges of female tigers to be about 20 km^2 in the Sundarbans region indicating a high density of tigers in the area (Barlow et al., 2011). Even if the tiger home ranges are double, the Bangladesh Sundarbans could support 100–150 breeding females or 300–500 tigers overall (Barlow, 2009). Using the pugmark sign, a comprehensive tiger census on 2004 estimated 440 Bengal tigers in the Bangladesh Sundarbans (Barlow et al., 2008; Ahmad et al., 2009). The latest census using camera traps, however, have identified tiger population to be between 83 and 130 individuals in the Bangladesh Sundarbans (Dey et al., 2015). The camera traps used in the last census,

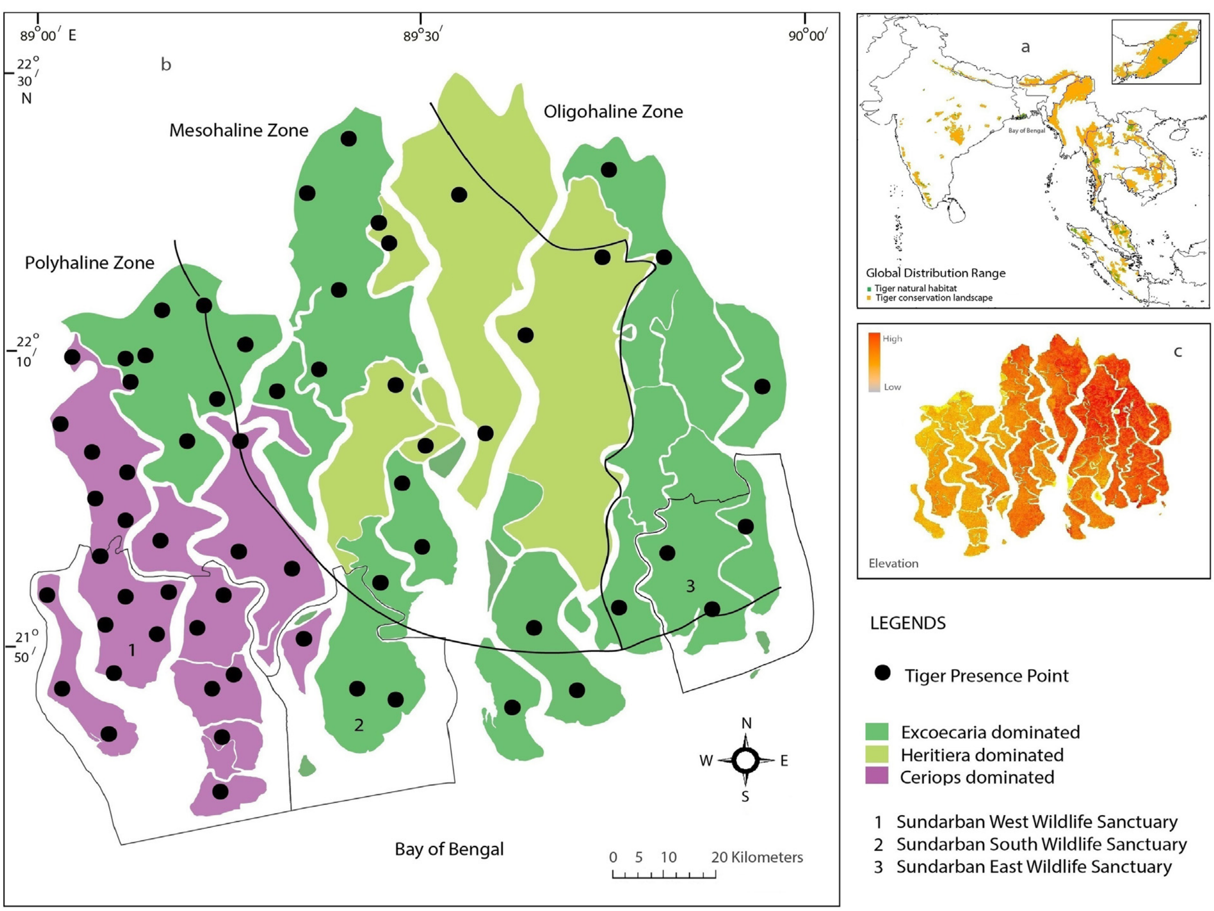

Fig. 2. (a) The global distribution of tigers (Source: IUCN, 2015); (b) the Bangladesh Sundarbans with major vegetation zones, salinity zones and location of three major wildlife sanctuaries; and (c) topographic map of the Bangladesh Sundarbans.

however, were restricted to only a few locations, therefore, we used the occupancy data of Bengal tiger based on pugmark sign. For the present study, we used 66 tiger presence points (see Fig. 2) as described in Barlow et al. (2008) based on their intensive survey in the area.

2.3. Bioclimatic variables and data sources

We used 19 gridded temperature and precipitation parameters downscaled to 1 km^2 (30 s) spatial resolution derived from WorldClim (www.worldclim.com) as our baseline climate conditions (Hijmans et al., 2005; Table 1). These parameters are biologically more meaningful to define the eco-physiological tolerances of most species (Graham and Hijmans, 2006). The vegetation data of the Sundarbans were obtained from the Bangladesh Forest Department. We superimposed three major wildlife sanctuaries to assess the ability of existing terrestrial protected area networks to support Bengal tiger habitats in the area. For elevation, we used a digital elevation model (DEM) at 30 m resolution from NASA's Shuttle Radar Topography Mission (SRTM). We performed a multicollinearity test to check any cross-correlation among predictor variables (Table S3). In the final model, we used only nine bioclimatic variables and vegetation type (VEG) of the Sundarbans (Table 1). All data were processed using ArcMap (version 10.2).

2.4. Climate projections and scenarios

We used two general climate circulation trajectories (representative concentration pathways or RCP) as developed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014). The trajectories are based on plausible ranges of global greenhouse gas emissions and/or concentrations, where RCP8.5 is a substantially rising pathway and RCP6.0 is an intermediate pathway (Makino et al., 2015). To predict the future distribution of Bengal tiger in the Sundarbans, we used two reference year, i.e., 2050 and 2070.

Globally, sea level rise is likely to occur in the ranges of 38–73 cm for RCP6.0 and 52–98 cm for RCP8.5 by 2100 (IPCC, 2013). To predict the effect of sea level rise in tiger habitats in the Sundarbans, four different SLR scenarios were developed (see Table 2). We used digital terrain modeling techniques using a current DEM of the area for our projections.

Table 1
List of bioclimatic variables used in the preliminary and final models of our study.

Parameter	Description	Final model	
		Yes	No
BIO1	Annual mean temperature	x	
BIO2	Mean diurnal range		x
BIO3	Isothermality	x	
BIO4	Temperature seasonality	x	
BIO5	Max temperature of warmest month	x	
BIO6	Min temperature of coldest month	x	
BIO7	Temperature annual range		x
BIO8	Mean temperature of wettest quarter		x
BIO9	Mean temperature of driest quarter		x
BIO10	Mean temperature of warmest quarter	x	
BIO11	Mean temperature of coldest quarter		x
BIO12	Annual precipitation	x	
BIO13	Precipitation of wettest month		x
BIO14	Precipitation of driest month		x
BIO15	Precipitation seasonality		x
BIO16	Precipitation of wettest quarter		x
BIO17	Precipitation of driest quarter		x
BIO18	Precipitation of warmest quarter	x	
BIO19	Precipitation of coldest quarter		x
VEG	Vegetation type	x	

Table 2
Projected sea level rise under different climate scenarios used in this study.

Scenario	Sea level rise (cm)	
	2050	2070
RCP6.0	30	60
RCP8.5	40	80

2.5. Habitat distribution modeling

We used maximum entropy (MaxEnt) species distribution model based on the principle of maximum entropy to model the potential species distribution (Phillips et al., 2006). It is widely used for species distribution modeling and superior than any other tool used for modeling species distribution (Hernandez et al., 2006; Kramer-Schadt et al., 2013). Another advantage of MaxEnt is, it is developed to model species distribution using presence-only data when few presence records are available for a target species (Pearson et al., 2007; Kumar and Stohlgren, 2009).

We executed a total of 500 runs for our model, building with a threshold rule of 10 percentile training presence. We evaluated models using 'Area Under the Receiver Operating Characteristic (ROC) Curve' or 'Area Under Curve (AUC)', considering models with AUC ≥ 0.8 to be good to excellent (Lobo et al., 2008). As per suggested by Elith et al. (2011), we applied an omission error of 10%, thereby, areas only within 90% presence data were considered as suitable habitats in our models. We prepared the current and projected habitat suitability maps of Bengal tiger using threshold raster layers, and calculated their likely habitat loss.

2.6. Model limitation and uncertainties

Climate changes are likely to affect the frequency and magnitude of climate extremes in the near future (Butt et al., 2016) and may also possess synergistic effect with other biodiversity threats (see- Brook et al., 2008; Ockendon et al., 2014). Considering only climate exposure in species distribution models, therefore, could lead to an underestimation or overestimation of future suitable habitats of Bengal tiger in the Sundarbans area. Other than the extreme climatic events (e.g., cyclone) (Harun-or-Rashid et al., 2009), poaching (Saif et al., 2016), human-wildlife conflict (Inskip et al., 2013), over-consumption of tiger prey species (Mohsanin et al., 2013) are also common in the Bangladesh Sundarbans and directly affecting the population of Bengal tiger in the area. The changes in total forest coverage in the Sundarbans over the last three decades although found to be nonsignificant (Giri et al., 2015; Joshi et al., 2016); changes in the vegetation pattern (Mukhopadhyay et al., 2015), invasive species (Biswas et al., 2007), salinity (Hoque et al., 2006) and sedimentation (Syvitski et al., 2009), however, are prevalent. In our models, we were not able to include these aspects due to scarce spatially explicit data for the Sundarbans area.

3. Results

3.1. Current distribution of Bengal tiger in the Sundarbans

Our model calibration ($AUC_{train} = 0.735$) and validation ($AUC_{test} = 0.9$) indicated a good performance of the model. Fig. 3 below shows the likely current distribution of Bengal tiger in the Bangladesh Sundarbans. Based on Jackknife estimates, precipitation of the warmest quarter (BIO18) mostly influences the Bengal tiger distribution in the area, which explained 42.6% variation in the model. Other bioclimatic and environmental variables influencing the Bengal tiger distribution in the Sundarbans forests included - vegetation type (VEG), maximum temperature of the warmest month (BIO5), isothermality (BIO3), annual

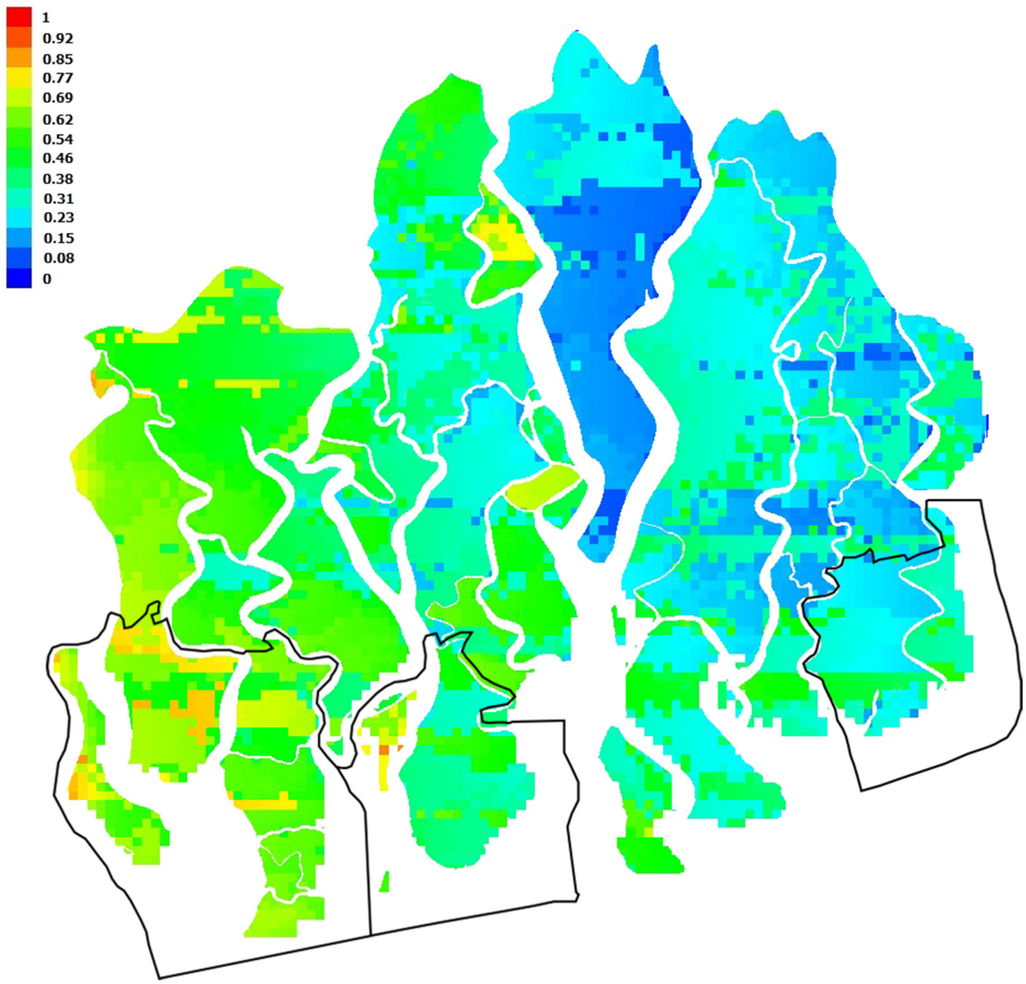

Fig. 3. Projected current distribution of Bengal tiger in the Bangladesh Sundarbans using MaxEnt. The colors closer to the red indicate a high probability of Bengal tiger presence in the area and vice-versa. The three wildlife sanctuaries are within the black borders.

mean temperature (BIO1) and mean temperature of the warmest quarter (BIO10) (Table 3). The remaining bioclimatic variables appeared to have no significant effect in determining the distribution of Bengal tiger in the area.

3.2. Impacts of climate change and sea level rise on Bengal tiger distribution in the Sundarbans

The distribution of Bengal tiger in Bangladesh Sundarbans with IPCC's RCP6.0 and RCP8.5 climate projections are shown in Fig. 4. In the figures, the colors closer to the red represent a greater chance of Bengal tiger persistence, whilst the color near to blue indicate unsuitable habitat for tiger. Sea level rise is likely to further deteriorate the situation by shrinking suitable tiger habitats in the area (Fig. 5). The projected habitat loss due to climate change will be 49.7% and 96.2% respectively by the year 2050 with IPCC's RCP6.0 and RCP8.5 scenario (Table 4). A complete loss of habitat is likely to happen only due to climate change by the year 2070 with RCP8.5 scenario. Although sea level rise continues to threaten the existence of Bengal tiger habitats in the area, the effect will be not as be pronounced as climate change (see Table 4). Due to the combined effect of climate change and sea level rise, there will be no remaining Bengal tiger habitat in the Sundarbans by the year 2070.

Table 3
Relative importance of different bioclimatic and environmental variables in Bengal tiger distribution in Bangladesh Sundarbans.

Variable	Percent contribution (%)	Permutation importance
Precipitation of warmest quarter	42.6	40.8
Vegetation	27.7	18.6
Maximum temperature of warmest month	12.7	24.1
Isothermality	12	10.7
Annnual mean temperature	5	5.7
Mean temperature of warmest quarter	0.1	0

3.3. Conservation of Bengal tiger in the Sundarbans

We observed a limited capacity of existing terrestrial protected areas network in the conservation of Bengal tiger in Sundarbans forests of Bangladesh. Fig. 6 below shows the projected suitable habitats of Bengal tiger within the existing protected areas of Bangladesh Sundarbans on 2050 and 2070 using IPCC's RCP6.0 and RCP8.5 scenario. Apparently, two wildlife sanctuaries (i.e., Sundarban West and Sundarban South WS) contribute largely to the conservation of Bengal tiger in the area where a viable tiger population is likely to occur. only in one wildlife sanctuary (i.e., Sundarban West WS). The three new wildlife sanctuaries (i.e., Dudhmukhi WS, Chandpai WS and Dhangamari WS) that have been declared recently in the area are not strategically important for

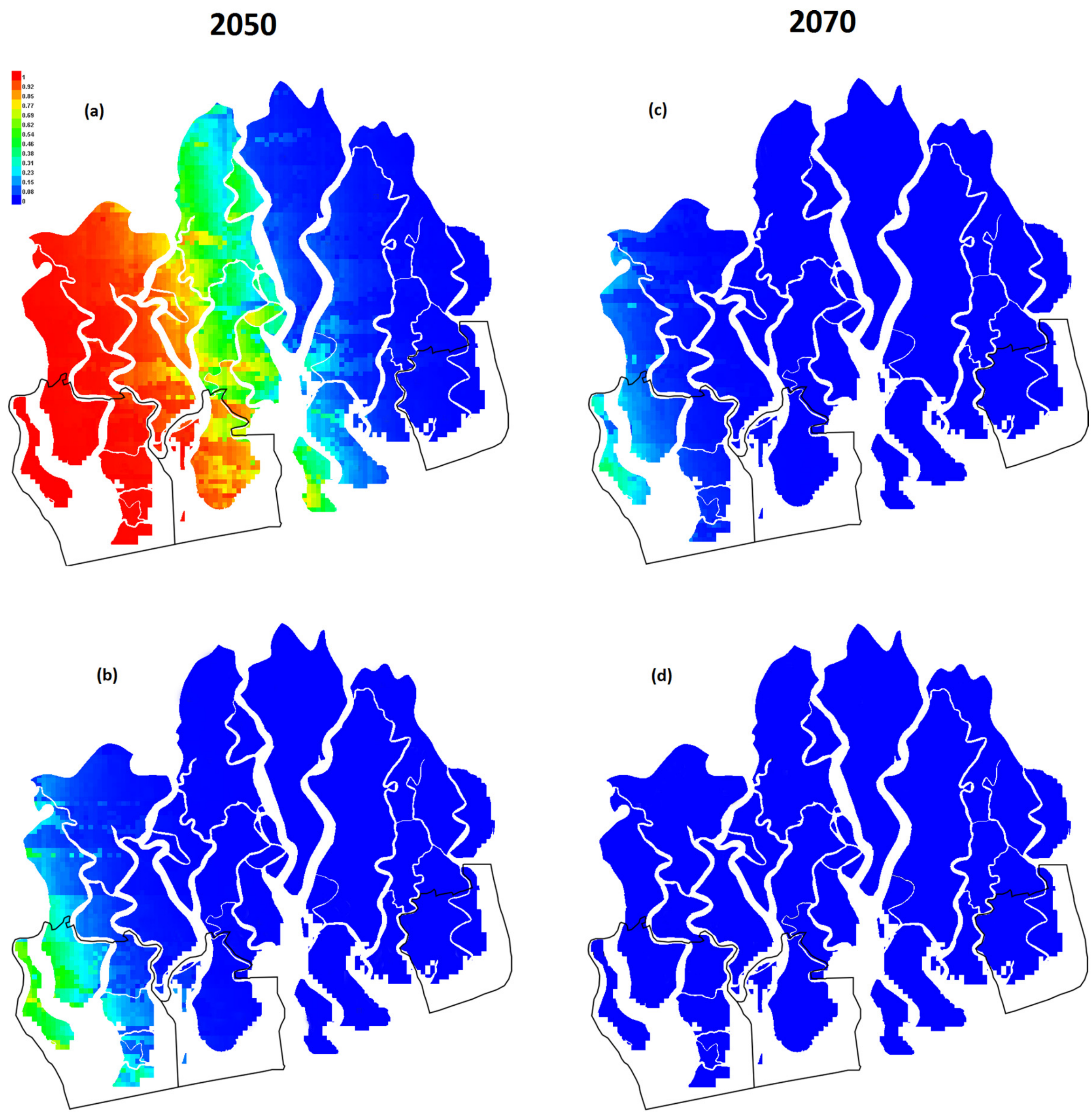

Fig. 4. Likely distribution of Bengal tiger in the Bangladesh Sundarbans – (a) distribution on 2050 with IPCC's RCP6.0 scenario, (b) distribution on 2050 with RCP8.5 scenario, (c) distribution on 2070 with RCP6.0 scenario, and (d) distribution on 2050 with RCP8.5 scenario. The three wildlife sanctuaries are within the black borders.

the conservation of Bengal tiger due to their size (170–560 ha), location and target species.

4. Discussion

4.1. The future of Bengal tiger in the Sundarbans

We found a dramatic decline of suitable Bengal tiger habitats in Bangladesh Sundarbans using IPCC's RCP6.0 and RCP8.5 scenario (Fig. 4). Climate change has a more pronounced effect on Bengal tiger habitats than that of only sea level rise in the area. Together climate change and sea level rise will further exacerbate the situation in Bangladesh Sundarbans (see Table 4). In fact, our model predicted that by 2070 there will be no remaining suitable Bengal tiger habitat in the Sundarbans. Loucks et al. (2010) also reported a sizable reduction in suitable Bengal tiger habitat's in the Sundarbans with rising sea level. Our study though confirms a complete loss of tiger habitats in the Sundarbans by 2070. We found that the effect of climate change will always be profound than that of only sea level rise in the area.

Globally, many wildlife species have already responded to changing climate and sea level rise (see- Réale et al., 2003; Sinervo et al., 2010; Sheridan and Bickford, 2011; Ockendon et al., 2014; Auer and King, 2014; Struebig et al., 2015a; Alamgir et al., 2015; Costion et al., 2015; Wich et al., 2016), although the relative contribution of different climatic parameters in the distribution and abundance of various wildlife species still remains undefined (Colwell et al., 2008; Pimm, 2008; Mantyka-Pringle et al., 2012; Maxwell et al., 2016). In recent years, it is widely acknowledged that, other than climatic factors, interaction with other species and environmental factors are also reponsible to a greater extent, for the changes and losses of biodiversity at both the local and global levels (Thomas et al., 2004; Brook et al., 2008; Mantyka-Pringle et al., 2012; Uddin et al., 2013; Alamgir et al., 2015; Segan et al., 2015). These statements are in accordance with the findings of our study.

There are contradictions about the global and regional projections of the future rate of SLR (Pacifici et al., 2015). Bindoff et al. (2007) predicted that sea level will rise by 4 mm year annually, with estimates of global SLR ranging between 0.22 and 0.42 ± 0.15 m by the mid-2090s, although, more recent global projections suggested that the

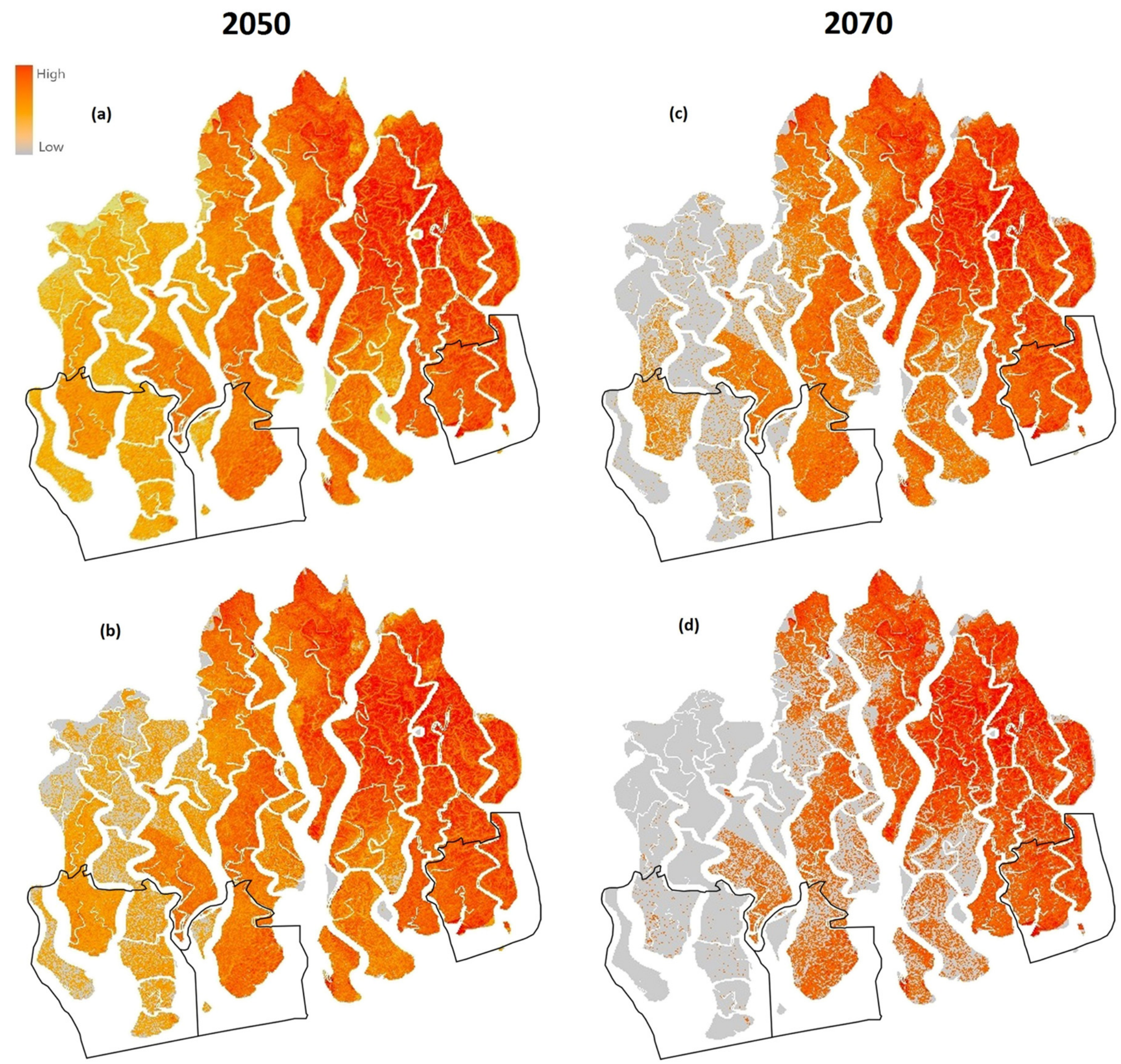

Fig. 5. Projected sea level rise impacts in the Bangladesh Sundarbans – (a) areas after IPCC's RCP6.0 projection for 2050, (b) areas after IPCC's RCP8.5 projection for 2050, (c) areas after IPCC's RCP6.0 projection for 2070, (d) areas after IPCC's RCP8.5 projection for 2070. The three wildlife sanctuaries are within the black borders.

rate of SLR will be greater than previously thought (see – Hansen, 2007; Rahmstorf, 2007; Pfeffer et al., 2008; Pethick and Orford, 2013).

The future of many wildlife species will largely depend on their ability to adapt or tolerate to a wide range of climatic conditions, e.g., limited or heavy rainfall, a change in temperature, etc. (see – Feeley and Silman, 2010; Ramirez-Villegas et al., 2014; Alamgir et al., 2015). Among our selected bio-climatic variables, six temperature parameters (out of 10) and two rainfall parameters were included in the model. Our model projection suggested a denser Bengal tiger population currently in the western part of the Sundarbans which is also reported in Ahmad et al. (2009) and Barlow (2009). In our final MaxEnt model, precipitation in the warmest quarter (BIO18), and four temperature parameters (i.e., maximum temperature of warmest month (BIO5), isothermality (BIO3), annual mean temperature (BIO1) and mean temperature of the warmest quarter (BIO10)) contributed respectively 42.6%, 12.7%, 12%, 5%, 0.1%. Vegetation type (VEG) was another important environmental parameter explaining the variation in Bengal tiger habitat distribution in the area and contributed 27.7% in our final MaxEnt model.

Using both IPCC scenarios, we found a moderate effect of sea level rise on suitable Bengal tiger habitats in 2050, contributing respectively 5.42% and 11.3% habitat loss in the area. Since it was not possible for us to include SLR in our MaxEnt model, we superimposed sea level rise data with our MaxEnt outputs using digital elevation models. Using higher resolution (i.e., sub-meter) DEM, Loucks et al. (2010), however, found that a 28 cm rise in sea level in the area might result in a 96% loss of suitable Bengal tiger habitats, which is quite high compared to our findings. A higher resolution DEM, in our study, therefore,

Table 4
Bengal tiger habitat loss in Bangladesh Sundarbans due to climate change and sea level rise on 2050 and 2070.

Scenario	Description	2050		2070	
		Percent (%)	Area (km2)	Percent (%)	Area (km2)
RCP6.0	Only climate change	49.7	2401.5	99.4	4803.1
	Only SLR	5.42	261.9	28.5	1377.1
	Climate change and SLR	54.2	2618.9	100	4832.0
RCP8.5	Only climate change	96.2	4648.4	100	4832.0
	Only SLR	11.3	546.1	48.9	2362.8
	Climate change and SLR	96.9	4682.2	100	4832.0

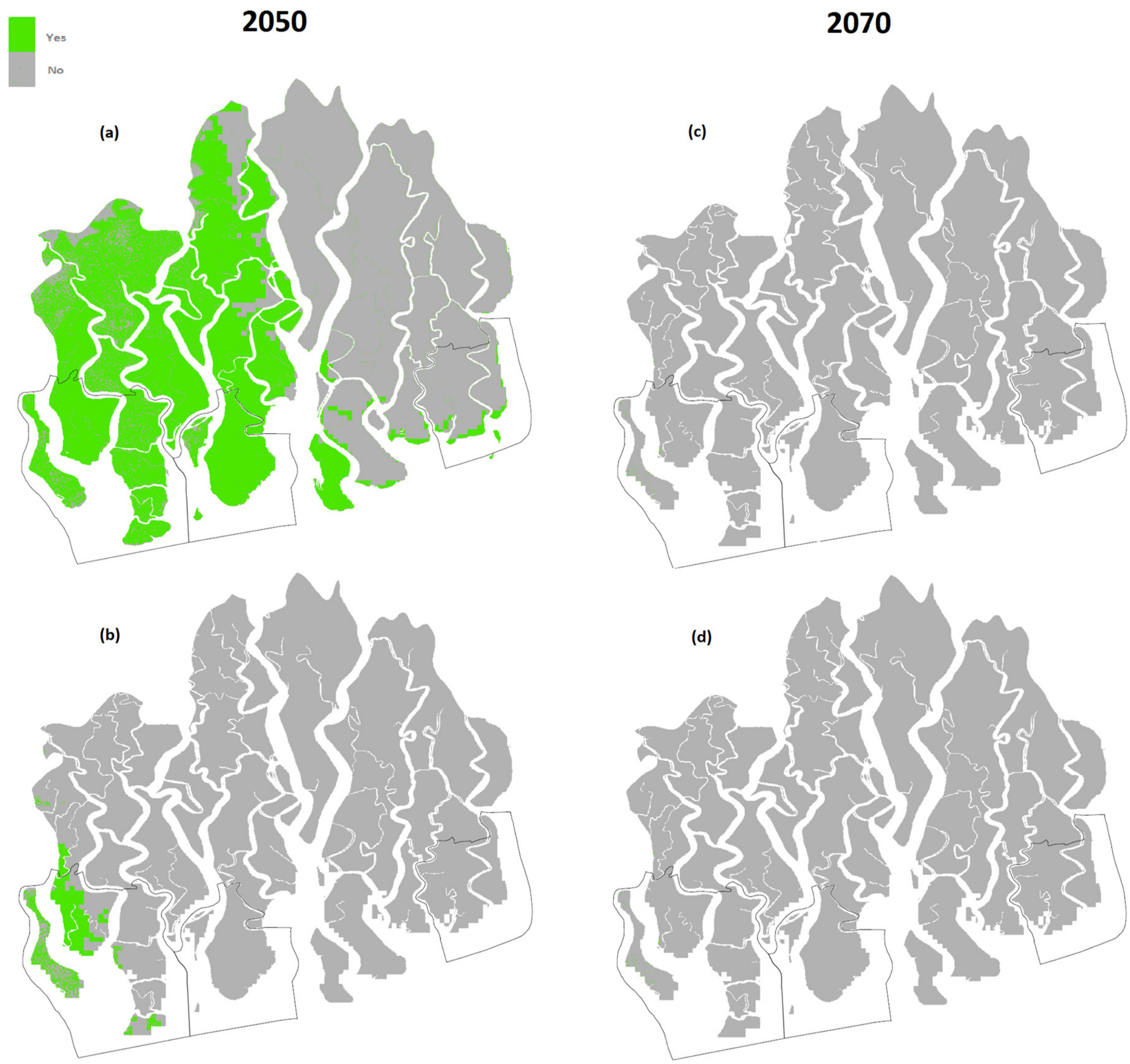

Fig. 6. Congruence of climate change and sea level rise impacts on Bengal tiger habitats in the Bangladesh Sundarbans: (a) suitable habitats on 2050 using IPCC's RCP6.0 scenario, (b) suitable habitats on 2050 using IPCC's RCP8.5 scenario, (c) suitable habitats on 2070 using IPCC's RCP6.0 scenario, and (d) suitable habitats on 2070 using IPCC's RCP8.5 scenario.

could have yielded a major decline of suitable Bengal tiger habitat in the Sundarbans area.

Our model suggested a total extinction of Bengal tiger in Bangladesh Sundarbans due to climate change in 2070 using RCP8.5 emission pathway, which is a more substantially increasing climate change pathway when compared with RCP6.0 (Makino et al., 2015). Climate change alone will result in a reduction of 96.2% and 99.4% Bengal tiger habitats in the area in 2050 and 2070, respectively using IPCC's RCP8.5 and RCP6.0 scenarios. Together, climate change and SLR will contribute to the total loss of Bengal tiger habitats in the area by 2070 using both RCP6.0 and RCP8.5 scenario (see Table 4).

4.2. Conservation and management implications

Globally, climate change has challenged our approach to building protected area networks because it may act as the only refuge for threatened wild fauna in near future and likely to drive accelerating shifts in species distributions (Carvalho et al., 2011). In Bangladesh Sundarbans, together the three main wildlife sanctuaries (i.e., Sundarban West, South and East) covers approximately 23% of the total Sundarbans reserved forest owned by Bangladesh Forest Department. This figure is still inadequate, considering the fact that, Sundarbans is the largest wild habitat of Bengal habitat and only place where tigers are adapted to live in mangrove ecosystems (Mukul et al., 2017, 2018).

Poaching of tigers, water divergence in upstream areas, wood collection, fishing, and harvesting of other aquatic resources also pose serious threats to Bengal tigers in the Sundarbans area (Aziz et al., 2013, 2017). In the last five years, the Forest Department and law enforcers have recovered three tiger cubs and twelve tiger skins from the area (Roy, 2015). A high level of tiger-human conflict manifested in human-killing, livestock depredation, and ultimately the retribution killings of tigers by affected local communities also common in the Sundarbans (Ahmad et al., 2009). According to Inskip et al. (2013), at least three tigers are killed per year in the Sundarbans area as a result of tiger-human conflict.

The main prey species of Bengal tiger in Sundarbans is the spotted deer (*Axis axis*), although it also feeds on wild boar (*Sus scrofa*), rhesus monkey (*Macaca mulatta*), and certain aquatic fishes and crabs (Reza et al., 2001). Poaching and unsustainable collection of prey species, therefore, further reduces the capacity of the Sundarbans forest to support a tiger population (Ahmad et al., 2009). In addition to these, forest degradation, climate-driven catastrophes like cyclones, invasive species, industrial development in surrounding areas, and expanding water transport networks within the Sundarbans area also causing threats to the survival of the last remaining Bengal tigers in the area and needs

to be taken into consideration for any successful tiger conservation effort (see – Biswas et al., 2007; Harun-or-Rashid et al., 2009; Hossain et al., 2016; Ishtiaque et al., 2016; Alamgir et al., 2017; Castillo et al., 2017).

5. Conclusion

Bangladesh, being situated in a low lying floodplain delta, is one of the most vulnerable countries due to climate change and associated events. Our study clearly indicates a rapid decline in the Bengal tiger population and suitable tiger habitats in the Sundarbans area by 2050, and a complete loss of this species by 2070. We have found that climate change always had a greater effect than that of only sea level rise alone on suitable Bengal tiger habitats. Even though, tiger poaching, human-tiger conflicts, decline in prey species and death of tiger due to other catastrophic events including disease were not considered in this analysis, both climate change and sea level rise were found enough to decimate this iconic species from the Sundarbans – the only region where tiger is adapted to live in a mangrove environment, by the end of this century. In addition to that, poor protected area coverage for tiger conservation is another issue hindering the future of Bengal tiger in the area.

Undesirably, both climate change and SLR is an unavoidable process affecting most of the global ecosystems and species. The government of Bangladesh, in such circumstances, should prioritize tiger conservation by designating more areas for tiger conservation, creating corridors for transboundary tiger movements, continues with strict monitoring and law enforcement to control illegal human activity in the area, avoid unplanned development in the vicinity, and raise public awareness to control human-tiger conflicts in the area. Future conservation actions should also consider possible climate change and SLR in the Sundarbans area together with tiger prey abundance and their response to climatic shifts.

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Appendix A. Supplementary data

Additional information related to this article regarding major vegetation types in the Bangladesh Sundarbans (Table S1), area distribution by elevation (Table S2), and correlation matrix between bioclimatic variables used in our study (Table S3) can be found in Appendix A (available online at: https://doi.org/10.1016/j.scitotenv.2019.01.383).

References

Ahmad, I.U., Greenwood, C.J., Barlow, A.C.D., Islam, M.A., Hossain, A.N.M., Khan, M.M.H., Smith, J.L.D., 2009. Bangladesh Tiger Action Plan 2009–2017. Bangladesh Forest Department, Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh.

Alamgir, M., Mukul, S.A., Turton, S., 2015. Modelling spatial distribution of critically endangered Asian elephant and Hoolock gibbon in Bangladesh forest ecosystems under a changing climate. Appl. Geogr. 60, 10–19.

Alamgir, M., Campbell, M.J., Sloan, S., Goosem, M., Clements, G.R., Mahmoud, M.I., Laurance, W.F., 2017. Economic, socio-political and environmental risks of road development in the tropics. Curr. Biol. 27, 1130–1140.

Apan, A., Cadavid, L.S., Maraseni, T.N., Salmo, S.G., Castillo, J.A.A., 2017. The rate, extent and spatial predictors of forest loss (2000—2012) in the terrestrial protected areas of the Philippines. Appl. Geogr. 81, 32–42.

Aryal, S., Cockfield, G., Maraseni, T.N., 2015. Perceived changes in climatic variables and impacts on the transhumance system in the Himalayas. Clim. Dev. 8, 435–446.

Aryal, A., Shrestha, U.B., Ji, W., Ale, S.B., Shrestha, S., Ingty, T., Maraseni, T.N., Cockfield, G., Raubenheimer, D., 2016a. Predicting the distributions of predator (snow leopard) and prey (blue sheep) under climate change in the Himalaya. Ecol. Evol. 6, 4065–4075.

Aryal, A., Lamsal, R.P., Ji, W., Raubenheimer, D., 2016b. Are there sufficient prey and protected in Nepal to sustain an increasing tiger population? Ethol. Ecol. Evol. 28, 117–120.

Auer, S.K., King, D.I., 2014. Ecological and life-history traits explain recent boundary shifts in elevation and latitude of western North American songbirds. Glob. Ecol. Biogeogr. 23, 867–875.

Aziz, A., Paul, A.R., 2015. Bangladesh Sundarbans: present status of the environment and biota. Diversity 7, 242–269.

Aziz, A., Barlow, A.C.D., Greenwood, C.C., Islam, A., 2013. Prioritizing threats to improve conservation strategy for the tiger Panthera tigris in the Sundarbans reserve Forest of Bangladesh. Oryx 47, 510–518.

Aziz, M.A., Tollington, S., Barlow, A., Goodrich, J., Shamsuddoha, M., Islam, M.A., Groombridge, J.J., 2017. Investigating patterns of tiger and prey poaching in the Bangladesh Sundarbans: implications for improved management. Glob. Ecol. Conserv. 9, 70–81.

Barlow, A.C.D., 2009. The Sundarbans Tiger: Adaptation, Population Status, and Conflict Management. (PhD Thesis). University of Minnesota.

Barlow, A.C.D., Ahmed, M.I.U., Rahman, M.M., Howlader, A., Smith, A.C., Smith, J.L.D., 2008. Linking monitoring and intervention for improved management of tigers in the Sundarbans of Bangladesh. Biol. Conserv. 141, 2031–2040.

Barlow, A.C.D., Smith, J.L.D., Ahmad, I.U., Hossain, A.N.M., Rahman, M., Howlader, A., 2011. Female tiger Panthera tigris home range size in the Bangladesh Sundarbans: the value of this mangrove ecosystem for the species' conservation. Oryx 45, 125–128.

Bellard, C., Leclerc, C., Hoffmann, B.D., Courchamp, F., 2016. Vulnerability to climate change and sea-level rise of the 35th biodiversity hotspot, the forests of East Australia. Environ. Conserv. 43, 79–89.

Bindoff, N.L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J.M., Gulev, S., Hanawa, K., Le Quere, C., Levitus, S., Nojiri, Y., Shum, C.K., Talley, L.D., Unnikrishnan, A.S., 2007. Observations: Oceanic Climate Change and Sea Level. In: Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., Chen, Z. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA, pp. 385–432.

Biswas, S.R., Choudhury, J.K., Nishat, A., Rahman, M.M., 2007. Do invasive plants threaten the Sundarbans mangrove forest of Bangladesh? For. Ecol. Manag. 245, 1–9.

Brook, B.W., Sodhi, N.S., Bradshaw, C.J.A., 2008. Synergies among extinction drivers under global change. Trends Ecol. Evol. 23, 453–460.

Butt, N., Possingham, H.P., Rios, C.D.L., Maggini, R., Fuller, R.A., Maxwell, S.L., Watson, J.E.M., 2016. Challenges in assessing the vulnerability of species to climate change to inform conservation actions. Biol. Conserv. 199, 10–15.

Canonizado, J.A., Hossain, M.A., 1998. Integrated Forest Management Plan for the Sundarbans Reserved Forest. Mandala Agricultural Development Corporation and Ministry of Environment and Forest, Dhaka, Bangladesh.

Carvalho, S.B., Brito, J.C., Crespo, E.G., Watts, M.E., Possingham, H.P., 2011. Conservation planning under climate change: toward accounting for uncertainty in predicted species distributions to increase confidence in conservation investments in space and time. Biol. Conserv. 144, 2020–2030.

Castillo, J.A.A., Apan, A., Maraseni, T.N., Salmo, S.G., 2017. Estimation and mapping of above-ground biomass of mangrove forests and their replacement land uses in the Philippines using sentinel imagery. ISPSR J. Photogramm. 134, 70–85.

Chamaille-Jammes, S., Massot, M., Aragon, P., Clobert, J., 2006. Global warming and positive fitness response in mountain populations of common lizards *Lacerta vivipara*. Glob. Chang. Biol. 12, 392–402.

Choudhury, A.M., 1968. Working Plan of the Sundarban Forest Division for the Period 1960–61 to 1979–80. East Pakistan Government Press, Dhaka (82 pp).

Colwell, R.K., Brehm, G., Cardelús, C.L., Gilman, A.C., Longino, J.T., 2008. Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. Science 322, 258–261.

Costion, C.M., Simpson, L., Pert, P.L., Carlsen, M.M., Kress, W.J., Crayn, D., 2015. Will tropical mountaintop plant species survive climate change? Identifying key knowledge gaps using species distribution modelling in Australia. Biol. Conserv. 191, 322–330.

Dawson, T.P., Jackson, S.T., House, J.I., Prentice, I.C., Mace, G.M., 2011. Beyond predictions: biodiversity conservation in a changing climate. Science 332, 53–58.

Dey, T.K., Kabir, M.J., Ahsan, M.M., Islam, M.M., Chowdhury, M.M.R., Hassan, S., Roy, M., Qureshi, Q., Naha, D., Kumar, U., Jhala, Y.V., 2015. First phase Tiger status report of Bangladesh Sundarbans. Wildlife Institute of India and Bangladesh Forest Department, Ministry of Environment and Forests. Government of the Peoples Republic of Bangladesh, Dhaka.

Dinerstein, E., Wikramanayake, E., Robinson, J., Karanth, U., Rabinowitz, A., Olson, D., Mathew, T., Hedao, P., Connor, M., Hemley, G., Bolze, D., 1997. A Framework for Identifying High Priority Areas and Actions for the Conservation of Tigers in the Wild. World Wildlife Fund and Wildlife Conservation Society, Washington, D.C.

Dinerstein, E., Loucks, C., Heydlauff, A., Wikramanayake, E., Bryja, G., Forrest, J., Ginsberg, J., Klenzendorf, S., Leimgruber, P., O'Brien, T., Sanderson, E., Seidensticker, J., Songer, M., 2006. Setting Priorities for the Conservation and Recovery of Wild Tigers: 2005–2015. A User's Guide. WWF, WCS, Smithsonian, and NFWF-STF, Washington, D.C. New York.

Dinerstein, E., Loucks, C., Wikramanayake, E., Ginsberg, J., Sanderson, E., Seidensticker, J., Forrest, J., Bryja, G., Heydlauff, A., Klenzendorf, S., Leimgruber, P., Mills, J., O'brien,

T.G., Shrestha, M., Simons, R., Songer, M., 2007. The fate of wild tigers. Bioscience 57, 508–514.
Elith, J., Phillips, S.J., Hastie, T., Dudik, M., Chee, Y.E., Yates, C.J., 2011. A statistical explanation of MaxEnt for ecologists. Divers. Distrib. 17, 43–57.
Ericson, J.P., Vorosmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2005. Effective Sea-level rise and deltas: causes of change and human dimension implications. Glob. Planet. Chang. 50, 63–82.
Feeley, K.J., Silman, M.R., 2010. Land-use and climate change effects on population size and extinction risk of Andean plants. Glob. Chang. Biol. 16, 3215–3222.
Garcia, R.A., Burgess, N.D., Cabeza, M., Rahbek, C., Araújo, M.B., 2012. Exploring consensus in 21st century projections of climatically suitable areas for African vertebrates. Glob. Chang. Biol. 18, 1253–1269.
Giri, C., Long, J., Abbas, S., Murali, R.M., Qamer, F.M., Pengra, B., Thau, D., 2015. Distribution and dynamics of mangrove forests of South Asia. J. Environ. Manag. 148, 101–111.
Gopal, B., Chauhan, M., 2006. Biodiversity and its conservation in the Sundarban mangrove ecosystem. Aquat. Sci. 68, 338–354.
Graham, C.H., Hijmans, R.J., 2006. A comparison of methods for mapping species ranges and species richness. Glob. Ecol. Biogeogr. 15, 578–587.
Hansen, J.E., 2007. Scientific reticence and sea level rise. Environ. Res. Lett. 2, 024002.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., et al., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
Harun-or-Rashid, S., Biswas, S.R., Böcker, R., Kruse, M., 2009. Mangrove community recovery potential after catastrophic disturbances in Bangladesh. For. Ecol. Manag. 257, 923–930.
Heller, N.E., Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biol. Conserv. 142, 14–32.
Hernandez, P.A., Graham, C.H., Master, L.L., Albert, D.L., 2006. The effect of sample size and species characteristics on performance of different species distribution modeling methods. Ecography 29, 773–785.
Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.
Hoque, M.A., Sarkar, M.S.K.A., Khan, S.A.K.U., Moral, M.A.H., Khurram, A.K.M., 2006. Present status of salinity rise in Sundarbans area and its effect on Sundari (*Heritiera fomes*) species. Res. J. Agric. Biol. Sci. 2, 115–121.
Hossain, A.N.M., Barlow, A., Barlow, C.G., Lynam, A.J., Chakma, S., Savini, T., 2016. Assessing the efficacy of camera trapping as a tool for increasing detection rates of wildlife crime in tropical protected areas. Biol. Conserv. 201, 314–319.
Ifthekar, M.S., Islam, M.R., 2004. Managing mangroves in Bangladesh: a strategy analysis. J. Coast. Conserv. 10, 139–146.
Ifthekar, M.S., Saenger, P., 2008. Vegetaion dynamics in the Bangladesh Sundarbans mangroves: a review of forest inventories. Wetl. Ecol. Manag. 16, 291–312.
Inskip, C., Ridout, M., Fahad, Z., Tully, R., Barlow, A., Barlow, C.G., Islam, M.A., Roberts, T., MacMillan, D., 2013. Human-Tiger conflict in context: risks to lives and livelihoods in the Bangladesh Sundarbans. Hum. Ecol. 41, 169–186.
Intergovernmental Panel on Climate Change (IPCC), 2013. Climate Change 2013: The Physical Science Basis. Cambridge University Press, UK, Summary for Policymakers.
IPCC, 2014. Climate change 2014: synthesis report. In: Pachauri, R., Meyer, L. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva, Switzerland).
Ishtiaque, A., Myint, S.W., Wang, C., 2016. Examining the ecosystem health and sustainability of the world's largest mangrove forest using multi-temporal MODIS products. Sci. Total Environ. 569–570, 1241–1254.
Islam, S., Rahman, M., Chakma, S., 2014. Plant diversity and forest structure of the three protected areas (wildlife sanctuaries) of Bangladesh Sundarbans: Current status and management strategies. In: Faridah-Hanum, I., et al. (Eds.), Mangrove Ecosystems of Asia, 127. Springer, New York.
IUCN, 2015. Red list of Bangladesh, volume 2: Mammals. International Union for Conservation of Nature (IUCN). Dhaka, Bangladesh, Bangladesh Country Office.
Joshi, A.R., Dinerstein, E., Wikramanayake, E., Anderson, M.L., Olson, D., Jones, B.S., Seidensticker, J., Lumpkin, S., Hansen, M.C., Sizer, N.C., Davis, C.L., Palminteri, S., Hahn, N.R., 2016. Tracking changes and preventing loss in critical tiger habitat. Sci. Adv. 2, e1501675.
Kaeslin, E., Redmond, I., Dudley, N., 2012. Wildlife in a changing climate. FAO Forestry Paper 167. United Nations (FAO), Rome, Food and Agriculture Organization of the.
Khan, R. (Ed.), 2013. Sundarban: Rediscovering Sundarban, the Mangrove Beauty of Bangladesh. Nymphea Publication, Dhaka, Bangladesh.
Kitchener, A.C., Dugmore, A.J., 2000. Biogeographical change in the tiger, *Panthera tigris*. Anim. Conserv. 3, 113–124.
Kramer-Schadt, S., Niedballa, J., Pilgrim, J.D., Schreoder, B., Lindenborn, J., Reinfelder, V., et al., 2013. The importance of correcting for sampling bias in MaxEnt species distribution models. Divers. Distrib. 19, 1366–1379.
Kumar, S., Stohlgren, T.J., 2009. Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. J. Ecol. Nat. Environ. 1, 94–98.
Lobo, J.M., Jiménez-Valverde, A., Real, R., 2008. AUC: a misleading measure of the performance of predictive distribution models. Glob. Ecol. Biogeogr. 17, 145–151.
Loucks, C., Barber-Meyer, S., Hossain, M.A.A., Barlow, A., Chowdhury, R.M., 2010. Sea level rise and tigers: predicted impacts to Bangladesh's Sundarbans mangroves, A letter. Clim. Chang. 98, 291–298.
Luo, S.J., Kim, J.H., Johnson, W.E., van der Walt, J., Martenson, J., et al., 2004. Phylogeography and genetic ancestry of tigers (*Panthera tigris*). PLoS Biol. 2, 2275–2293.
Makino, A., Klein, C.J., Possingham, H.P., Yamano, H., Yara, Y., Ariga, T., et al., 2015. The effect of applying alternate IPCC climate scenarios to marine reserve design for range changing species. Conserv. Lett. 8, 320–328.
Mantyka-Pringle, C.S., Martin, T.G., Rhodes, J.R., 2012. Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. Glob. Chang. Biol. 18, 1239–1252.
Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E.M., 2016. Biodiversity: the ravages of guns, nets and bulldozers. Nature 536, 143–145.
McGregor, T., 2010. Tigers of the Sundarbans. In: Tilson, R., Nyhus, P.J. (Eds.), Tigers of the World – The Science, Politics, and Conservation of *Panthera tigris*, 2nd edition Academic Press, USA, pp. 345–347.
Ministry of Environment and Forests (MoEF), 2016. Assessment of Sea Level Rise on Bangladesh Coast through Trend Analysis. MoEF, Dhaka, Bangladesh.
Mohsanin, S., Barlow, A.C.D., Greenwood, C.J., Islam, M.A., Kabir, M.M., Rahman, M.M., Howlader, A., 2013. Assessing the threat of human consumption of tiger prey in the Bangladesh Sundarbans. Anim. Conserv. 16, 69–76.
Moritz, C., Agudo, R., 2013. The future of species under climate change: resilience or decline? Science 341, 504–508.
Mukhopadhyay, A., Mondal, P., Barik, J., Chowdhury, S.M., Ghosh, T., Hazra, S., 2015. Changes in mangrove species assemblages and future prediction of the Bangladesh Sundarbans using Markov chain model and cellular automata. Environ. Sci.: Processes Impacts 17, 1111–1117.
Mukul, S.A., Rashid, A.Z.M.M., Khan, N.A., 2017. Forest protected area systems and biodiversity conservation in Bangladesh. In: Mukul, S.A., Rashid, A.Z.M.M. (Eds.), Protected Areas: Policies, Management and Future Directions. Nova Science Publishers, New York, pp. 157–177.
Mukul, S.A., Biswas, S.R., Rashid, A.Z.M.M., 2018. Biodiversity in Bangladesh. In: Pullaiah, T. (Ed.), Global Biodiversity, Vol. 1: Selected Countries in Asia. Apple Academic Press, Canada, pp. 93–107.
Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328, 1517–1520.
Ockendon, N., Baker, D.J., Carr, J.A., White, E.C., Almond, R.E.A., Amano, T., Bertram, E., Bradbury, R.B., Bradley, C., Butchart, S.H.M., Doswald, N., Foden, W., Gill, D.J.C., Green, R.E., Sutherland, W.J., Tanner, E.V.J., Pearce-Higgins, J.W., 2014. Mechanisms underpinning climatic impacts on natural populations: altered species interactions are more important than direct effects. Glob. Chang. Biol. 20, 2221–2229.
Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M., et al., 2015. Assessing species vulnerability to climate change. Nat. Clim. Chang. 5, 215–224.
Pearson, R.G., Raxworthy, C.J., Nakamura, M., Peterson, A.T., 2007. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. J. Biogeogr. 34, 102–117.
Pethick, J., Orford, J.D., 2013. Rapid rise in effective sea-level in Southwest Bangladesh: its causes and contemporary rates. Glob. Planet. Chang. 111, 237–245.
Pfeffer, W.T., Harper, J.T., O'Neel, S., 2008. Kinematic constraints on glacier contributions to 21st-century sea-level rise. Science 321, 1340–1343.
Phillips, S.J., Anderson, R.P., Schapire, R.E., 2006. Maximum entropy modeling of species geographic distributions. Ecol. Model. 190, 231–259.
Pimm, S.L., 2008. Climate change or habitat loss—which will kill more species? Curr. Biol. 18, 117–119.
Rahmstorf, S., 2007. A semi-empirical approach to projecting Future Sea-level rise. Science 315, 368–370.
Ramirez-Villegas, J., Cuesta, F., Devenish, C., Peralvo, M., Jarvis, A., Arnillas, C.A., 2014. Using species distributions models for designing conservation strategies of tropical Andean biodiversity under climate change. J. Nat. Conserv. 22, 391–404.
Ranganathan, J., Chan, K.M.A., Karanth, K.U., Smith, J.L.D., 2008. Where can tigers persist in the future? A landscape-scale, density-based population model for the Indian subcontinent. Biol. Conserv. 141, 67–77.
Réale, D., McAdam, A.G., Boutin, S., Berteaux, D., 2003. Genetic and plastic responses of a northern mammal to climate change. Proc. Biol. Sci. 270, 591–596.
Reza, A.H.M.A., Feeroz, M.M., Islam, M.A., 2001. Food habits of the Bengal tiger (*Panthera tigris tigris*) in the Sundarbans. Bangladesh J. Zool. 29, 173–179.
Roy, P., 2015. Wildlife trafficking sees sharp rise in Bangladesh. The Daily Star available online at. http://www.thedailystar.net/frontpage/wildlife-trafficking-sees-sharp-rise-152602.
Saif, S., Russell, A.M., Nodie, S.I., Inskip, C., Lahann, P., Barlow, A., Barlow, C.G., Islam, M.A., MacMillan, D.C., 2016. Local usage of Tiger parts and its role in Tiger killing in the Bangladesh Sundarbans. Hum. Dimens. Wildl. 21, 95–110.
Sarwar, M.G.M., 2013. Sea-level rise along the coast of Bangladesh. In: Shaw, R., Mallick, F., Islam, A. (Eds.), Disaster Risk Reduction Approaches in Bangladesh. Springer, Japan, pp. 217–231.
Segan, D.B., Hole, D.G., Donatti, C.I., Zganjar, C., Martin, S., Butchart, S.H.M., Watson, J.E.M., 2015. Considering the impact of climate change on human communities significantly alters the outcome of species and site-based vulnerability assessments. Divers. Distrib. 21, 1101–1111.
Sheridan, J.A., Bickford, D., 2011. Shrinking body size as an ecological response to climate change. Nat. Clim. Chang. 1, 401–406.
Siddiqi, N.A, 2001. Mangrove forestry in Bangladesh. Institute of Forestry and Environmental Sciences. University of Chittagong, Bangladesh.
Sinervo, B., Méndez-de-la-Cruz, F., Miles, D.B., Heulin, B., Bastiaans, E., et al., 2010. Erosion of lizard diversity by climate change and altered thermal niches. Science 328, 894–899.
Stanton, J.C., Shoemaker, K.T., Pearson, R.G., Akçakaya, H.R., 2015. Warning times for species extinctions due to climate change. Glob. Chang. Biol. 21, 1066–1077.
Struebig, M.J., Fischer, M., Gaveau, D.L.A., Meijaard, E., Wich, S.A., Gonner, C., Sykes, R., Wilting, A., Kramer-Schadt, S., 2015a. Anticipated climate and land-cover changes reveal refuge areas for Borneo's orang-utans. Glob. Chang. Biol. 21, 2891–2904.
Struebig, M.J., Wilting, A., Gaveau, D.L.A., Meijaard, E., Smith, R.J., Fischer, M., Metcalfe, K., Kramer-Schadt, S., 2015b. Targeted conservation to safeguard a biodiversity hotspot from climate and land-cover change. Curr. Biol. 25, 372–378.

Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Tannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nat. Geosci. 2, 681–686.

Thapa, A., Shah, K.B., Pokheral, C.P., Paudel, R., Adhikari, D., Bhattarai, P., Cruz, N.J., Aryal, A., 2017. Combined land cover changes and habitat occupancy to understand corridor status of Laljhadi-Mohana wildlife corridor, Nepal. Eur. J. Wildl. Res. 63, 83.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., et al., 2004. Extinction risk from climate change. Nature 427, 145–148.

Uddin, M.B., Steinbauer, M.J., Jentsch, A., Mukul, S.A., Beierkuhnlein, C., 2013. Do environmental attributes, disturbances and protection regimes determine the distribution of exotic plant species in Bangladesh forest ecosystem? For. Ecol. Manag. 303, 72–80.

Visser, M.E., Both, C., 2005. Shifts in phenology due to global climate change: the need for a yardstick. Proc. R. Soc. B 272, 2561–2569.

Walston, J., Robinson, J.G., Bennett, E.L., Breitenmoser, U., Fonseca, G.A.B., et al., 2010a. Bringing the Tiger back from the brink—the six percent solution. PLoS Biol. 8, e1000485.

Walston, J., Karanth, K.U., Stokes, E., 2010b. Avoiding the unthinkable: What will it cost to prevent tigers becoming extinct in the wild? Global Tiger Initiative. D.C. and Wildlife Conservation Society, USA (126p)

Wich, S.A., Singleton, I., Nowak, M.G., Utami Atmoko, S.S., Nisam, G., Arif, S.M., Putra, R.H., Ardi, R., Fredriksson, G., Usher, G., Gaveau, D.L.A., Kühl, H.S., 2016. Land-cover changes predict steep declines for the Sumatran orangutan (*Pongo abelii*). Sci. Adv. 2, e1500789.

Wikramanayake, E.D., Dinerstein, E., Robinson, J.G., Karanth, K.U., Rabinowitz, A., et al., 1998. An ecology-based method for defining priorities for large mammal conservation: the tiger as case study. Conserv. Biol. 12, 865–868.

World Wildlife Fund (WWF), 2016. Wild tiger numbers increase to 3,890.Available online at. http://tigers.panda.org/t2/wild-tigers-numbers-increase-to-3890/ (date of access: April 15, 2016).